W/Z+γ measurement @ ATLAS

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Motivation

- \( W(l\nu)/Z(ll)+\gamma \) production measurement:
  - ISR: t/u-channel
  - s-channel TGC
  - FSR
  - Gluon/quark fragmentation

- Searching anomalous triple gauge couplings (aTGC):
  - W magnetic dipole and electric quadrupole moment
    \[
    \mu_W = \frac{e}{2M_W} (2 + \Delta \kappa_\gamma + \lambda_\gamma)
    \]
    \[
    Q_W = -\frac{e}{M_W^2} (1 + \Delta \kappa_\gamma - \lambda_\gamma)
    \]
  - \( ZZ\gamma/Z\gamma\gamma \) prohibited by SM

- Prior-LHC results
  + D0, 4.2 fb\(^{-1}\) \( W\gamma \), PRL107(2011)241803

+ CDF, 5 fb\(^{-1}\) \( Z\gamma \), PRL107(2011)051802
+ D0, 6.2 fb\(^{-1}\) \( Z\gamma \), PRD85(2012)052001
Event Selection

- **ATLAS 7TeV 1fb$^{-1}$ (35pb$^{-1}$) data:**
  - Lepton:
    + e/μ $p_T$>25GeV, detector fiducial $|\eta|$ coverage; isolated in calorimeter;
    + Tight electron identification
  - W/Z events:
    + MET>25GeV, MT($l\nu$)>40GeV; M($ll$)>40GeV
  - Photon:
    + $p_T$>15GeV, detector fiducial $|\eta|$ coverage;
    + Isolated in calorimeter
    + Tight photon identification
    + FSR suppression $dR(l,\gamma)>0.7$
    + Simulation corrected to $Z \rightarrow ll\gamma$ data
  - Jet:
    + $p_T$>30GeV, $|\eta|<4.4$, $dR(j,\gamma/lepton)>0.6$
    - Inclusive (≥0jet) vs.
    - Exclusive (==0jet)

- ✓ ATLAS 35pb$^{-1}$ result as JHEP 1109,072
- ✓ ATLAS 1.02fb$^{-1}$ result as arXiv:1205.2531
ISR/FSR vs. $p_T(\gamma)$ cut:

ISR: $M(ll\gamma) > M_Z$

FSR: $M(ll\gamma) \leq M_Z$

High photon $p_T$ cut to suppress FSR as

$Z\gamma$: $p_T(\gamma) > 15, \ 60\text{GeV}$; $W\gamma$: $p_T(\gamma) > 15, \ 60, \ 100\text{GeV}$
Electroweak background derived from simulation

Dominant background, $W+jet$ has to be estimated from data
W/Z+jet background

- 2D sideband jet → “γ” background estimation:

  - **Photon Identification**: based on calorimeter shower-shape
  
  - **Photon Isolation**: 

    \[ \text{Iso} E_T^{30} = \left[ \sum_{dR<0.3} E_T^i \right] - E_T^\gamma \]

- Standard Photon Identification
  - (Isolated) 
  - (Non-isolated)
  - C
    - (Control Region)
    - A 
      - (Signal Region)
    - D 
      - (Control Region)

- Background estimation:

  \[ N_A = N_{W\gamma}^A + N_{W\text{jet}}^A \]
  
  \[ N_{B/C/D} = N_{B/C/D}^{W\text{jet}} \]
  
  \[ N_{A}^{W\text{jet}} = N_{B}^{W\text{jet}} \cdot \frac{N_{C}^{W\text{jet}}}{N_{D}^{W\text{jet}}} \]
Jet+$\gamma$ background in $W\gamma$

- Date-driven jet $\Rightarrow$ “$e/\mu$” estimation:
  1) jet+$\gamma$: real $\gamma$; non-isolated lepton from heavy b/c decay;
  2) Control region: MET<20GeV to extract faked “$e/\mu$” isolation shape

![Graph showing MET vs. isolation 2-d sideband for W(ev)$\gamma$ events.](chart.png)
Photon $E_T$ spectrum:

$W(l\nu)\gamma$ inclusive

$Z(ll)\gamma$ inclusive

* Signal distribution normalized to the number of extracted data
Number of jet distribution:

\[ Z(ll)\gamma : p_T(\gamma) > 60\text{GeV} \]

\[ W(l\nu)\gamma : p_T(\gamma) > 100\text{GeV} \]

Inclusive (\(\geq 0\text{jet}\)) vs. Exclusive (\(= 0\text{jet}\))
Cross section measurement

\[ \sigma_{pp \rightarrow l\nu \gamma(l+l-\gamma)}^{\text{ext-fid}} = \frac{N_{W\gamma(Z\gamma)}^{\text{sig}}}{A_{W\gamma(Z\gamma)} \cdot C_{W\gamma(Z\gamma)} \cdot L} \]

- Detector Acceptance
- Experimental selection efficiency
- Luminosity \(1.024 \pm 3.8 \text{ fb}^{-1}\)

- Unfold detector efficiency:
  + Correction factor \(C_{W\gamma(Z\gamma)} \sim 40 - 60\%\)
  + Systematic \(\delta_C \sim 10\%\), dominated by photon identification & jet energy scale
Compared against MCFM

- Compare to SM prediction:
  - Estimated from Alpgen/Sherpa
  - + Extend detector fiducial to a uniform lepton $|\eta|$ coverage
  - + Theoretical uncertainty on acceptance $\delta_{Theo.} \sim 1-3\%$

Unfold for detector acceptance:

- $A_{W(Z)\gamma} = \frac{N_{\text{fiducial}}}{N_{\text{extended-fiducial}}}$

- Compared against **MCFM** (ISR + FSR + QCD NLO)
Differential cross sections

1) Photon $p_T > 15, 60, 100$ GeV; 2) Inclusive ($\geq 0$ jet) vs. Exclusive (=0 jet)

- The Exclusive measurements are consistent with MCFM predictions (SM NLO)
- The $W\gamma$ Inclusive are higher than MCFM, especially in high $p_T(\gamma)$ region → high order effects ($\text{NNLO}$ and beyond)
Anomalous couplings

$+ \alpha_{\text{TGC}} h_{3/4}^{V} : ZV\gamma$ electric dipole / magnetic quadrupole transition moment

$+ \text{non-zero } \alpha_{\text{TGC}} \text{ will result in increasing of } W/Z+\gamma \text{ cross section, especially in high photon } p_T \text{ region}$

$h_i^V = \frac{h_{i0}^V}{(1 + \hat{s} / \Lambda^2)^n}$
Extract $ZV\gamma$ aTGC:

- Exclusive $E_T(\gamma)^{>60\text{GeV}}$ measurement $\sigma_{Z\gamma}^{\text{obs}}$ against aTGC hypotheses $\sigma_{Z\gamma}^{\text{aTGC}}$

+ Bayesian probability with nuisance parameters to set limits
Extract $WW\gamma$ aTGC:

$WW\gamma$ aTGC: $\Delta\kappa_\gamma, \lambda_\gamma$

Exclusive $E_T(\gamma) > 100\text{GeV}$ measurement $\sigma_{WW\gamma}^{\text{obs}}$ against aTGC $\sigma_{WW\gamma}^{\text{aTGC}}$ hypotheses
The differential cross section $W(l\nu)\gamma/Z(ll)\gamma$ measured @ 1fb$^{-1}$ 7TeV ATLAS:

- Exclusive (=0jet) measurement is consistent with SM NLO
- High order effect (NNLO and beyond) is observed in $W\gamma$ inclusive ($\geq$0jet) data, especially in high photon $p_T(\gamma)>60\text{GeV}$ region

Limits on anomalous TGC couplings derived from high photon $p_T$ spectrum:

- $WW\gamma$ aTGC results better than the existing Tevatron limits
Backup slides
Signal event yield

- **W(lν)γ:**

<table>
<thead>
<tr>
<th>Region</th>
<th>$E_T^γ &gt; 15$ GeV</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_{jet} \geq 0$</td>
<td>$N_{jet} = 0$</td>
</tr>
<tr>
<td>$N^{obs}_{Wγ}$</td>
<td>2649</td>
<td>3621</td>
</tr>
<tr>
<td>$W + jets$</td>
<td>439 ± 108</td>
<td>685 ± 162</td>
</tr>
<tr>
<td>$γ + jets$</td>
<td>255 ± 58</td>
<td>67 ± 16</td>
</tr>
<tr>
<td>EW</td>
<td>405 ± 53</td>
<td>519 ± 67</td>
</tr>
<tr>
<td>$tt$</td>
<td>85 ± 11</td>
<td>152 ± 20</td>
</tr>
<tr>
<td>$N^{sig}_{Wγ}$</td>
<td>1465 ± 139</td>
<td>2198 ± 183</td>
</tr>
</tbody>
</table>

- **Z(υυ)γ:**

<table>
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</thead>
<tbody>
<tr>
<td></td>
<td>$N_{jet} \geq 0$</td>
<td>$N_{jet} = 0$</td>
</tr>
<tr>
<td>$N^{obs}_{Zγ}$</td>
<td>514</td>
<td>634</td>
</tr>
<tr>
<td>$Z + jets$</td>
<td>43.7 ± 16.5</td>
<td>56.8 ± 16.2</td>
</tr>
<tr>
<td>$N^{BG}_{Zγ}$</td>
<td>471 ± 28</td>
<td>578 ± 29</td>
</tr>
<tr>
<td>$N^{sig}_{Zγ}$</td>
<td>471 ± 28</td>
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</tbody>
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- Dominate background as $W+jet(“γ”), γ+jet (“e”), Z(υυ)$

- Dominate background as $Z+jet$